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Demarcating exercise intensity domains in freestyle swimming; is there an alternative to incremental step test and beats below HR_{MAX} method?

ABSTRACT

Critical power derived from the 3-min all-out test (3MT) was recently utilized to estimate the exercise intensity boundaries in competitive cyclists. Considering that physiological testing is challenging in swimming, the purpose of this study was to examine whether critical speed (CS) derived from 3MT could be used for the same purpose in swimming. The second aim was to assess the accuracy of the 50-40 and 30-20 beats below maximal heart rate method (BBM), currently utilized by swimming coaches to demarcate boundaries between moderate-heavy and heavy-severe exercise, respectively. Thirteen swimmers completed an incremental step test (IST) and 3MT **in freestyle** to establish speeds at: lactate threshold (LT); lactate turnpoint (LTP); maximum aerobic speed (S_{MAX}); and CS. Using linear regression through origin, speeds at LT, LTP and S_{MAX} were predicted at 89, 98 and 104% of CS derived from 3MT. There were no significant differences between threshold speeds derived from IST and 3MT ($p>0.05$), and nearly perfect correlations at LT (1.21 ± 0.06 ; 1.21 ± 0.06 m.s⁻¹; $r=0.92$) and LTP (1.33 ± 0.07 ; 1.33 ± 0.07 m.s⁻¹; $r=0.90$), and very large correlations at S_{MAX} (1.40 ± 0.06 ; 1.40 ± 0.07 m.s⁻¹; $r=0.88$; all $p<0.0001$). Speeds estimated at 50 (1.11 ± 0.08 m.s⁻¹) and 40BBM (1.17 ± 0.07 m.s⁻¹) were lower compared to LT, and speeds estimated at 30 (1.23 ± 0.07 m.s⁻¹) and 20BBM (1.29 ± 0.07 m.s⁻¹) were lower compared to LTP and CS (all $p<0.02$). The 3MT can therefore be used as an alternative to IST to estimate exercise intensity boundaries, in practical settings where resources or time might be limited. However, the BBM significantly underestimates speeds at LT, LTP and CS.

Key words: critical speed, 3-minute all-out, testing, training, swimming

INTRODUCTION

It is well established that the exercise intensity continuum comprises of four domains: moderate, heavy, severe, and extreme (4). The upper limit of moderate domain is set by the lactate threshold (LT) or gas exchange threshold (GET). The boundary between heavy and severe domains is typically set by critical power (CP)/speed (CS), maximal lactate steady state (MLSS), or lactate turnpoint (LTP) (8). The highest work rate that elicits maximal oxygen uptake ($\dot{V}O_{2MAX}$) is the boundary between severe and extreme domains (4).

The traditional approach to demarcating exercise intensity domains in swimming involves completion of an incremental step test (IST) (9). However, due to the resources, time and expertise required to complete this test, an IST is not regularly performed by swimming coaches coaching larger groups of competitive swimmers. Instead, generalized prescription of training zones based on a number of beats below maximal heart rate (BBM) is widespread practice amongst swimming coaches (table 1). However, considering the inter- and intra-individual differences in the way athletes respond to exercise, the effectiveness of the methods that utilize maximal heart rate (HR_{MAX}) alone to individualize training has been questioned (1,14).

****Insert Table 1 here****

Recently, a 3-min all-out test (3MT) has been proposed to demarcate the boundary between heavy and severe exercise intensity domains in multiple sports, including swimming (5, 20). To extend the utility of the 3MT, Francis et al. (11) utilized CP from 3MT to estimate the boundary between moderate and heavy exercise intensity domains, and approximated LT at 76% of cycling CP. However, this estimation was in contrast with the findings of Pettitt et al. (18), who observed GET at 90% of running CS. Considering the inherent differences in the bioenergetics of swimming compared to other modes of exercise (25), the estimation of LT

from swimming CS is likely to vary from those previously reported in cycling and/or running. Given the time-consuming and invasive nature of the tests utilized to establish the parameters demarcating exercise intensity domains, alongside the multidisciplinary (four strokes), technological and environmental constraints that apply to physiological testing in swimming, obtaining reliable estimates of all exercise intensity domains without the need for blood sampling in a single test would be appealing to swimming practitioners.

Therefore, the aim of the present study was to assess whether the CS derived from 3MT can be utilized to estimate the parameters demarcating the exercise intensity domains, when compared to those established in IST. Based on previous findings (11), **it was** hypothesized that the 3MT could be used to estimate the boundaries of the exercise intensity domains in a single test. The second aim of this study was to examine the accuracy of the 50-40 and 30-20 BBM that are currently utilized by swimming coaches to demarcate the boundary between moderate-heavy and heavy-severe exercise intensity domains, respectively.

METHODS

Experimental approach to the problem

The protocol consisted of four visits to the swimming pool. Firstly, the subjects performed a 200 m time trial (TT) which was used for the prescription of speed increments in the IST. As the subjects in this study regularly performed 3MT, the subjects were not asked to complete a familiarisation with this test. All swimmers completed a familiarisation trial with the IST. On separate days, subjects performed the IST and 3MT in a random order over a one week period. Each trial was preceded by a 5-min low-intensity warm-up and was followed by 5-min rest (28), and **the front crawl** (freestyle) technique was adopted in all tests. All trials were completed in a 50 m pool using a push-off start, flip turns, and occurred at the same time of day (± 1 h). Given the potential impact of nutrition and preceding exercise on the $[La^-]$ values

(8), all subjects and parents were provided with an information sheet explaining optimal nutrition and recovery strategies to maximise results of the testing. Training volume and intensity were reduced in the week of testing, and all subjects had a recovery session the evening prior to testing and had the morning off on the day of testing.

Subjects

Thirteen swimmers who were recruited from a performance squad of competitive swimmers (6 males, 7 females, age 16 ± 1 yrs (range: 15-17 yrs), body mass 63.7 ± 8.9 kg, height 175 ± 8 cm) volunteered to participate in this study, which had received approval from the Research Ethics Approval Committee for Health at the University of Bath. All subjects were national or international competitive swimmers, completing training volumes of ~ 45 km.week⁻¹, and had training histories of 8 ± 2 yrs. The participants had no known history of respiratory, cardiovascular, metabolic or musculoskeletal disease, and were not taking any medications that might have affected the variables under investigation. Prior to any testing all subjects and parents were informed of the protocol, risks and discomfort associated with the procedure and potential benefits, both verbally and in writing, and gave their written consent.

Procedures

Incremental step test

The first stage of the test started at the speed associated with 200 m TT minus 0.35 m.s⁻¹, and was increased in the subsequent stages by 0.05 m.s⁻¹ until exhaustion occurred (9). In-between 200 m steps, a 30 s rest interval was allowed for blood sampling ([La⁻] from an earlobe). Pace was controlled with a Finis Tempo Trainer (Finis Inc., California, USA) that was preprogrammed to the pace required to swim each 50 m in order to ensure that the swimmers swam their expected 200 m time evenly. Time to complete each 200 m stage (Finis Inc., 3 x 100 m, California, USA), [La⁻] (Lactate Plus, Nova Biomedical, Waltham, USA), rating of

perceived exertion (RPE, 1-10 Borg scale) and HR (A300, Polar, USA) were collected at the end of each 200 m stage.

Three-min all-out test

Subjects were asked to swim at an “all-out” swimming speed (i.e., as fast as you possibly can from the beginning of the test). To discourage pacing, the subjects were verbally-encouraged throughout the test and were not informed about the time-elapsed nor time-remaining. Each 3MT speed-time profile was visually inspected for pacing, and if increase in speed in the last 30 s of the test was observed, the swimmers were asked to repeat the test.

Swimming time splits were recorded using a stopwatch (Finis, 3 x 100 m, California, USA) at every 10 m by an experienced timekeeper. Ten meter stages were marked with fluorescent cones placed parallel to the swimmer’s lane at every 5 m along the pool deck to enable calculating split times as well as displacement (D) of the swimmer at 150 and 180 s. A 10 s countdown was given to the researcher that walked with a cone alongside a swimmer and placed a cone at 150 s and 180 s at the furthest point reached (i.e., a hand). Distance at 150 s (D_{150}) and 180 s (D_{180}) were recorded using a 50 meter tape measure placed parallel to the swimming lane and were used for the calculation of CS using the following formula (6):

$$CS_{3MT} (m \cdot s^{-1}) = (D_{180} - D_{150}) / 30$$

Determination of threshold speeds from the IST

The swimmers’ $[La^-]$ -velocity curves were constructed to obtain the following parameters:

1. LT_{IST} : the point at which $[La^-]$ started and continued to increase above the baseline concentration, via visual inspection from three independent researchers (4)
2. LTP_{IST} : the point at which $[La^-]$ started to increase exponentially, via visual inspection from three independent researchers in combination with a mathematical model adapted by Fernandes et al. (9)

3. $S_{\text{MAX-IST}}$: was defined as the highest speed of the 200 m stage in the IST
4. % Δ : difference between the speed at LT_{IST} and $S_{\text{MAX-IST}}$

Determination of threshold speeds using the BBM method

The highest HR recorded during IST was used as a HR_{MAX} . According to the method utilized by swimming coaches (table 1), HR_{MAX} was subsequently utilized to demarcate the boundary between moderate-heavy domains using 50 ($LT_{50\text{BBM}}$) and 40 BBM ($LT_{40\text{BBM}}$), and between heavy-severe domains using 30 ($LTP_{30\text{BBM}}$ / $CS_{30\text{BBM}}$) and 20 BBM ($LTP_{20\text{BBM}}$ / $CS_{20\text{BBM}}$).

Statistical Analyses

Statistical analyses were performed using SPSS Version 24.0 (SPSS Inc., Chicago, IL). One-way repeated-measures ANOVA was used to determine differences between $CS_{3\text{MT}}$, speed at LT_{IST} , LTP_{IST} , and $S_{\text{MAX-IST}}$. Main effects were compared using the Bonferroni correction. Bivariate correlation analysis was performed between $CS_{3\text{MT}}$ and speed at LT_{IST} , LTP_{IST} and $S_{\text{MAX-IST}}$. To simplify estimate calculations for threshold speeds when using $CS_{3\text{MT}}$, the linear regression between $CS_{3\text{MT}}$ and each exercise intensity threshold derived from the IST (i.e., LT_{IST} , LTP_{IST} , $S_{\text{MAX-IST}}$) was restricted to cross through origin (i.e., intercept was set to zero) (e.g., regression equation: $y = 0.8931x$, where x is $CS_{3\text{MT}}$ of participant and y is the point of interest [e.g. predicted LT speed], and slope can be interpreted as a percentage value if multiplied by 100) (11). To estimate the threshold speeds associated with investigated BBM methods, a regression equation describing the linear relationship between HR and speed was utilized. Differences between actual and predicted speeds at LT, LTP, CS and S_{MAX} were determined using paired-sample t-test. A Pearson correlation coefficient and a Bland-Altman analysis were also used to assess the relationships, bias and the limits of agreement (LOA) between actual and predicted speeds at LT, LTP, CS and S_{MAX} , as well as actual and predicted

HR at LT and LTP when using BBM method. The alternative method to the IST was considered significantly biased if the 95% confidence intervals (CI) for mean bias did not cross over zero. The acceptable LOA were defined *a priori* as 2% of the mean speed at LT, LTP, CS and S_{MAX} , based on the practical experience of the acceptable level of precision for coaches prescribing target times within training sessions (± 3 s for 200 m split). The acceptable LOA for HR were defined as 3% of the mean HR at LT and LTP (1). Default thresholds for correlations were 0.1, small; 0.3, moderate; 0.5, large; 0.7, very large; 0.9, nearly perfect. Effect size (ES) was calculated using Cohen's d (i.e., mean difference divided by pooled SD). For all tests, statistical significance was accepted at $p < 0.05$ level, with data presented as means \pm SD.

RESULTS

Mean speed data and pairwise comparisons for significant differences between speed at LT_{IST} , LTP_{IST} , CS_{3MT} and $S_{MAX-IST}$ are shown in table 2. The speed at LT_{IST} , LTP_{IST} , and CS_{3MT} were 86%, 95% and 96% of $S_{MAX-IST}$, respectively. The CS_{3MT} and LTP_{IST} occurred at 76 ± 14 and $62 \pm 12\% \Delta$, respectively. Table 2 also shows percentages of CS_{3MT} that were calculated through linear regression through origin analysis, and were used to predict speed at LT_{3MT} , LTP_{3MT} and $S_{MAX-3MT}$ for each swimmer.

Insert Table 2 here

Defining boundaries of exercise intensity domains using CS_{3MT}

The mean predicted speeds at LT_{3MT} , LTP_{3MT} and $S_{MAX-3MT}$ when using CS derived from 3MT are presented in table 3 alongside SEE, ES, CI, correlation, bias and LOA. Figure 1A-E demonstrates relationships and bias \pm 95% LOA between the threshold speeds derived from the IST and 3MT. There was no significant difference between the threshold speeds derived from the IST and 3MT ($p > 0.93$). There were significant correlations ($p < 0.0001$), and no significant bias between investigated threshold speeds derived from IST and 3MT. The 95%

LOA for LT, LTP and S_{MAX} were outside of the 2% threshold determined *a priori* as acceptable (table 3; figure 1A-E), however, 9 (for LTP) and 10 (for LT and S_{MAX}) out of 13 swimmers were within this threshold.

Insert Table 3 here

Insert Figure 1 here

Defining boundaries of exercise intensity domains using the BBM method

The mean predicted speeds at LT, LTP, CS, and mean predicted HR at LT and LTP derived from the investigated BBM method are illustrated in tables 4 and 5, respectively. Figure 2A-E illustrates the individual relationships between the threshold speeds derived from the IST (LT_{IST} , LTP_{IST}) and 3MT (CS_{3MT}), and investigated BBM. The investigated BBM method significantly underestimated the speed at LT_{IST} , LTP_{IST} and CS_{3MT} , and HR at LT_{IST} and LTP_{IST} ($p < 0.05$), and 95% LOA were outside of the 2% and 3% thresholds determined *a priori* as acceptable, respectively (tables 4 and 5).

Insert Table 4 here

Insert Table 5 here

Insert Figure 2 here

DISCUSSION

The principal finding of this study is that the CS derived from the 3MT can be used to estimate the boundaries of exercise intensity domains that are comparable to those derived from an IST in competitive swimmers. Additionally, the commonly-used BBM method significantly underestimated speed at LT_{IST} , CS_{3MT} and LTP_{IST} , and HR at LT_{IST} and LTP_{IST} . When expressed individually in relation to the LT_{IST} , CS_{3MT} and LTP_{IST} , the investigated BBM method covered wide ranges of exercise intensities that might be unacceptable in swimming, where the range

between exercise intensity domains is narrow (12). To our knowledge this is the first study to examine the utility of the 3MT to establish the exercise intensity boundaries, or to assess the accuracy of the BBM method to demarcate boundaries of exercise intensity domains in swimming.

Defining boundaries of exercise intensity domains using CS_{3MT}

Moderate-heavy exercise intensity domains

Using linear regression through origin, this study found that the speed at LT could be estimated at 89.31% of CS_{3MT} with a low SEE (0.03 m.s⁻¹; 2.2% of LT). This is in contrast to Francis et al. (11) who predicted the power output at LT at 76% of CP_{3MT} with SEE of 28 W (15% of LT) in cycling. This difference could be attributed to differences in bioenergetics between the modes of exercise (25). Indeed, Greco et al. (12) was the first study that found that the range of exercise intensities is very narrow in swimming, equivalent to a difference of only 0.22 m.s⁻¹ (~16 s per 100 m) between LT and S_{MAX}, which the authors attributed to the exponential relationship between energy cost and swimming speed (2, 3,16). The narrow range of exercise intensity domains was confirmed in the present study, equating to a difference of 0.19 m.s⁻¹ (~11 s per 100 m) between the speed at LT_{IST} and S_{MAX-IST}. The speed at LT_{IST} expressed relative to CS_{3MT} however differed between this study and the study of Greco et al. (12) (95% of MLSS), which is potentially due to the protocols utilized to establish the heavy-severe boundary. Indeed, whilst Greco et al. (12) utilized a traditional MLSS protocol, the 3MT was completed in the present study. However, considering the previous findings from Dekerle et al. (7) that reported that swimming CS occurs ~5.6% higher than MLSS, adjusting the speed at MLSS reported in Greco et al. (12) by 5.6%, would result in a similar position of LT in relation to the adjusted speed at MLSS as in the present study (i.e., 90%).

Similarly to Greco et al. (12), the speed at LT_{IST} occurred at 86% of $S_{MAX-IST}$. Although $\dot{V}O_2$ was not measured in this study, the findings suggest that the recruited highly-trained, though not elite swimmers would be able to sustain a high percentage of $\dot{V}O_{2MAX}$, similar to those reported in elite runners (i.e., 70-90% of $\dot{V}O_{2MAX}$) (13). Instead of attributing this to the level of swimmers recruited, Greco et al. (12) attributed this finding to the exponential relationship between energy cost and speed, as well as to the horizontal position adopted by swimmers, and the constant hydrostatic pressure from the micro-gravitational environment of water that could alter blood volume distribution, cardiac output and local blood flow that are likely to increase oxidative capacity (i.e., blood lactate removal).

Heavy-severe exercise intensity domains

On average, the CS_{3MT} and LTP_{IST} occurred at 96% and 95% of the $S_{MAX-IST}$, or 76 % Δ and 62% Δ , respectively. Using linear regression through origin, this study suggests that if LTP is of interest rather than CS , 98.27% of CS_{3MT} could be used to estimate the speed at LTP with a low SEE ($0.03 \text{ m}\cdot\text{s}^{-1}$, 2.6% of LTP). This is in contrast to the study of Greco et al. (12) who found $MLSS$ at a lower percentage of S_{MAX} ($88 \pm 2\%$) and % Δ ($26 \pm 10 \text{ \%}\Delta$). These differences could be attributed to the protocol utilized to establish the boundary between heavy-severe domains, as discussed previously. Alternatively, considering the exponential relationship between the energy cost and swimming speed, higher values of CS_{3MT} and LTP_{IST} when expressed in relation to $S_{MAX-IST}$ and as % Δ compared to those typically reported in moderately-trained population (i.e. 70-80% $\dot{V}O_{2MAX}$) and in cycling or running (i.e., 50% Δ) could be expected (12). Indeed, the position of both CS_{3MT} and LTP_{IST} in relation to $S_{MAX-IST}$ approached those reported in highly-trained runners and swimmers. Additionally, considering that CS and LTP do not only represent physiological transition thresholds but also biomechanical boundaries beyond which the stroke mechanics have been shown to become

compromised (3,16), this could further increase the energy cost of swimming with speed once swimmers pass these thresholds.

Severe-extreme exercise intensity domains

The S_{MAX} was predicted to occur at 103.51 % of CS_{3MT} with a low SEE ($0.03 \text{ m}\cdot\text{s}^{-1}$ or 2.1%) in the present study. This finding is similar to Francis et al. (11), however it is in contrast with Greco et al. (12), who reported the S_{MAX} at 114.5% of MLSS. This difference could be attributed to the fact that the MLSS generally occurs at a lower level compared to CS, as discussed earlier, and/or to the fact that Greco et al. (12) utilized a 400 m TT protocol without any prior fatiguing exercise to establish S_{MAX} . Alternatively, the difference could be attributed to the level of swimmers recruited. Indeed, the present study recruited a higher standard of competitive swimmers. Given that more highly-trained subjects tend to display LT and CS at a higher percentage of $\dot{V}O_{2MAX}$, and tend to possess greater technical ability, both of which affect the energy cost of swimming, the level of participants could explain differences in the position of the parameters demarcating the exercise intensity continuum into domains (13).

The BBM method

Following the prescription approach commonly utilized by swimming coaches, this study demonstrated that the BBM method provides an inaccurate demarcation of the boundaries between moderate-heavy and heavy-severe exercise intensity domains. Neither 50 nor 40 BBM provided an accurate demarcation of the speed or HR associated with LT_{IST} , equating to a **significant** difference of ~ 8 and ~ 3 s slower times per 100 m, or 17 and 7 bpm lower HR when compared to LT_{IST} , respectively. Similarly, neither 30 nor 20 BBM provided an accurate estimate of the speed associated with LTP_{IST} or CS_{3MT} , and HR associated with LTP_{IST} , equating to a **significant** difference of ~ 7 and ~ 3 s slower times per 100 m, or 17 and 7 bpm lower HR when compared to CS_{3MT} and LTP_{IST} , respectively.

The individual intensities corresponding to the investigated BBM methods and expressed relative to LT_{IST} , LTP_{IST} and CS_{3MT} covered wide ranges (81-105%), consistent with previous research studies (14). Considering the narrow range of exercise intensities in swimming, using the investigated BBM method to prescribe supposedly identical training might in reality result in training either below or above LT, LTP and CS between athletes. This could consequently result in different physiological response and limit of tolerance, therefore potentially leading to different training load and adaptations. Additionally, considering that exercise HR can vary by up to 3% (~6 bpm) (1) a day due to several factors (e.g. sleep, temperature, nutrition), this introduces further complications when training is based on HR_{MAX} alone. This could be amplified further if coaches choose to use age-predictive equations to calculate individuals' HR_{MAX} (23, 29). Indeed, applying the equations typically utilized by coaches (see table 1) to the recruited swimmers would result in 10 swimmers and 5 swimmers out of 13 having predicted HR_{MAX} outside of their actual HR_{MAX} range deemed as acceptable due to day-to-day variability of HR_{MAX} (i.e., ~2%, 4 bpm) (1), with some swimmers displaying as much as 20 bpm difference between actual and predicted HR_{MAX} . Therefore, considering that individualized training becomes increasingly important as the competitive level of athletes increases, the results from this study do not support the investigated BBM method as an effective tool to demarcate or prescribe exercise intensity in highly-trained swimmers. However, if this method is to be utilized, the results from the present findings suggest that the boundaries between moderate-heavy and heavy-severe domains can be estimated at 34 ± 9 BBM (or $83 \pm 5\% HR_{MAX}$) and 13 ± 5 BBM (or $93 \pm 3\% HR_{MAX}$) in highly-trained swimmers, respectively.

PRACTICAL APPLICATIONS

This study extended the utility of the 3MT, such that the parameters demarcating exercise intensity domains could be established with a single test and without the need for blood sampling. Whilst the threshold values observed in the current study (89.31 and 103.51% of the CS_{3MT} to approximate the speed at LT and S_{MAX} , respectively) are likely to be bespoke to the standard of swimmers and swimming stroke used in this work, the process outlined in this manuscript may be applied to other levels of swimmers and strokes in order to obtain relevant threshold values for those athletes and their specific strokes. The CS is directly determined from the 3MT, however if LTP (i.e., anaerobic threshold) is the point of interest instead, 98.27% of CS_{3MT} can be used. In applied settings, coaches are often limited by resource availability, time, and/or expertise, which might often force them to apply less valid (but more affordable) prescription methods (e.g., BBM) (22). Although the percentage estimations of CS_{3MT} for LT, LTP, S_{MAX} are likely to be unique to this study, the approach investigated in the current study could be used to enable coaches to regularly obtain more robust data in large groups of swimmers in a timely manner (~20 tested swimmers in 2 h session), and without the requirement for additional equipment or expertise. However, it is important to note that the proposed method assumes that the speed at LT remains constant in relation to CS_{3MT} , which might not be the case and thus constitutes a limitation of this study. However, considering that the prediction equation changed minimally (<1%) when different combinations of swimmers were removed from the model, this method could still provide a useful estimation of the speed at LT on a group basis. Additionally, considering that the speed at LT is not a main predictor for competitive swimming events that last <20 min, and that most coaches have a limited time and resources to establish the speed at LT through IST on a regular basis, this model could still provide a useful estimation of the speed at LT. However, if coaches work with marathon swimmers, where LT becomes a stronger predictor of performance, a more precise

measurement of the speed at LT would be recommended. Finally, although the approach investigated in the present study is similar to the BBM approach (i.e., estimates exercise intensity boundaries from CS only), the application of the CS model and 3MT in swimming training and performance is considerable, more affordable and arguably more performance-related compared to HR and BBM (17).

Considering the large training volumes that are typically performed in swimming (potentially to compensate for lack of individualisation), individualising training using the proposed method and CS model could allow for reduced volumes of training, which have been repeatedly identified as a cause for a wide array of overuse injuries (27), early specialisation and burnout (21) in swimming. Multiple studies, including the recent work of Courtright et al. (6), have challenged the “high volume” swimming coaching philosophy (15). Indeed, Courtright et al. (6) used the CS and finite capacity to swim above CS (i.e., D') parameters derived from the 3MT to prescribe personalized high intensity interval training in competitive swimmers for 4 weeks, and found that as little as two sessions of HIIT per week with the training volume of 900-3000 yards.week⁻¹ resulted in a significantly improved CS ($+0.04 \text{ m.s}^{-1}$), which represents a significant competitive advantage in swimming. Taking into account recently published literature focused on optimising the parameters demarcating exercise intensity domains in multiple sports, including in swimming (6, 24), future studies could apply the proposed model to highly-trained swimmers for an extended period of time (>6 weeks) in order to investigate what improvements, if any, can be obtained with a reduced volume of training compared to those typically observed in highly-trained swimmers (i.e., 40-70 km.week⁻¹).

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FIGURE CAPTIONS

Figure 1. Correlation and Bland-Altman analyses for differences in LT (A,B), LTP (C,D) and S_{MAX} (E,F) derived from the incremental step test (IST) and the 3-min all-out test (3MT). In the panels A, C and E, the *solid line* is the line of best-fit linear regression and the *dashed line* is the line of identity. In the panels B, D and F, the *solid horizontal lines* represent the mean difference between LT_{IST} and LT_{3MT} , LTP_{IST} and LTP_{3MT} , $S_{MAX-IST}$ and $S_{MAX-3MT}$, respectively, and the *dashed lines* represent the 95% limits of agreement; n=13.

Figure 2. Actual versus predicted speeds at (A, B) lactate threshold (LT), (C, D) critical speed (CS), (E, F) lactate turnpoint (LTP), using the investigated beats below HR_{MAX} method (BBM). The *solid line* is the line of best-fit linear regression and the *dashed line* is the line of identity; n=13.

Table 1. Description and training intensity measurement utilized by swimming coaches, national training centres and delivered as a part of swimming coaching curriculum in United Kingdom.

Training Zones	Name	Description	HR (bbm)	La (mM)	RPE
Zone 1	A1	<i>Aerobic Low Intensity</i> Base conditioning and technical training; warm-up and warm-down; Predominantly Fat Metabolism; largely slow-twitch fiber recruitment	> 50	< 2	< 9
	A2	<i>Aerobic Maintenance/ Development</i> Base aerobic training Improves cardio-respiratory system; enhances Lactate Removal	40-50	2-4	10-12
Zone 2	AT	<i>Anaerobic Threshold</i> Maximal Lactate Steady State where Lactate production = Lactate removal; Optimal intensity for development of aerobic capacity	20-30	3-6	14-15
Zone 3	VO ₂	<i>Aerobic Overload</i> High intensity work at approximately VO _{2max} ; This type of training includes Heart Rate and Vcrit sets; Improves VO _{2max} and aerobic power	5-20	6-12	17-19
Zone 4	LP	<i>Lactate Production</i> Training intensity results in the maximal speed of lactate build up This type of training includes Race Pace training Enhances rate of glycolytic energy production	5-15	8-15	17-19
	LT	<i>Lactate Tolerance</i> High intensity work with medium rest to improve buffering Developing the ability to tolerate lactate/ acidity in the muscle	0-10	12-20	19-20
Zone 5	Speed	<i>Sprinting –ATP-PC</i> High intensity, short duration, long rest repeats Designed to improve alactic energy production (ATP-PC), neuromuscular coordination and fast-twitch muscle fiber recruitment	N/A	N/A	N/A

bbm, beats below maximal heart rate (HR) of an individual; maximal heart rate is typically obtained via a maximal exercise, or predictive equations: “220-age” Fox et al. (10), “208-(0.7 x age)” Tanaka et al. (26); adapted from Peyrebrune (19)

Table 2. Comparison of the speed measures derived from the incremental step test and the 3-min all-out test.

	speed (m.s ⁻¹)	[La ⁻] (mmol.L ⁻¹)	HR (bpm)	<i>r</i> with CS _{3MT}	prediction (% of CS _{3MT})
LT_{IST}	1.21 ± 0.06	1.32 ± 0.40	164 ± 12	0.92*	89.31
LTP_{IST}	1.33 ± 0.07†	3.98 ± 1.12	185 ± 10	0.90*	98.27
S_{MAX-IST}	1.40 ± 0.06‡	10.73 ± 2.04	197 ± 8	0.88*	103.51
CS_{3MT}	1.35 ± 0.07†	11.22 ± 1.37	-	-	-

LT, lactate threshold; LTP, lactate turnpoint; S_{MAX}, maximum aerobic speed derived from the incremental step test (IST); CS, critical speed derived from the 3-min all-out test (3MT); [La⁻], blood lactate; HR, heart rate; bpm, beats per minute; † $p < 0.0001$ compared to LT_{IST}; ‡ $p < 0.001$ compared to all speed measures, * $p < 0.0001$ correlation (r); R² for linear regression through origin was 0.85, 0.82 and 0.68 for LT, LTP and S_{MAX}, respectively.

Table 3. Comparisons of the speeds at lactate threshold (LT), lactate turnpoint (LTP) and maximum aerobic speed (S_{MAX}) derived from the incremental step test (IST) and 3-min all-out test (3MT).

	Speed (m.s ⁻¹)	95% CI	ES	SEE (%)	<i>r</i> (95% CI)	Bias ± SD	95% LOA
LT_{3MT} vs LT_{IST}	1.21 ± 0.06	-0.01 to 0.01	-0.002	0.03 (2.2)	0.92* (0.75 to 0.98)	-0.00004 ± 0.02	-0.05 to 0.05†
LTP_{3MT} vs LTP_{IST}	1.33 ± 0.07	-0.02 to 0.02	0.00	0.03 (2.6)	0.90* (0.70 to 0.97)	-0.000001 ± 0.03	-0.06 to 0.06†
S_{MAX-3MT} vs S_{MAX-IST}	1.40 ± 0.07	-0.02 to 0.02	-0.02	0.03 (2.1)	0.88* (0.64 to 0.96)	-0.001 ± 0.03	-0.07 to 0.06†

* $p < 0.0001$ correlation (r); † limits of agreement (LOA) outside of the acceptable threshold of 2%; SEE, standard error of estimate; ES, effect size; CI, confidence interval

Table 4. Comparisons of the speeds at lactate threshold (LT), lactate turnpoint (LTP) and critical speed (CS) derived from the incremental step test (IST) and 3-min all-out test (3MT) to the investigated BBM method.

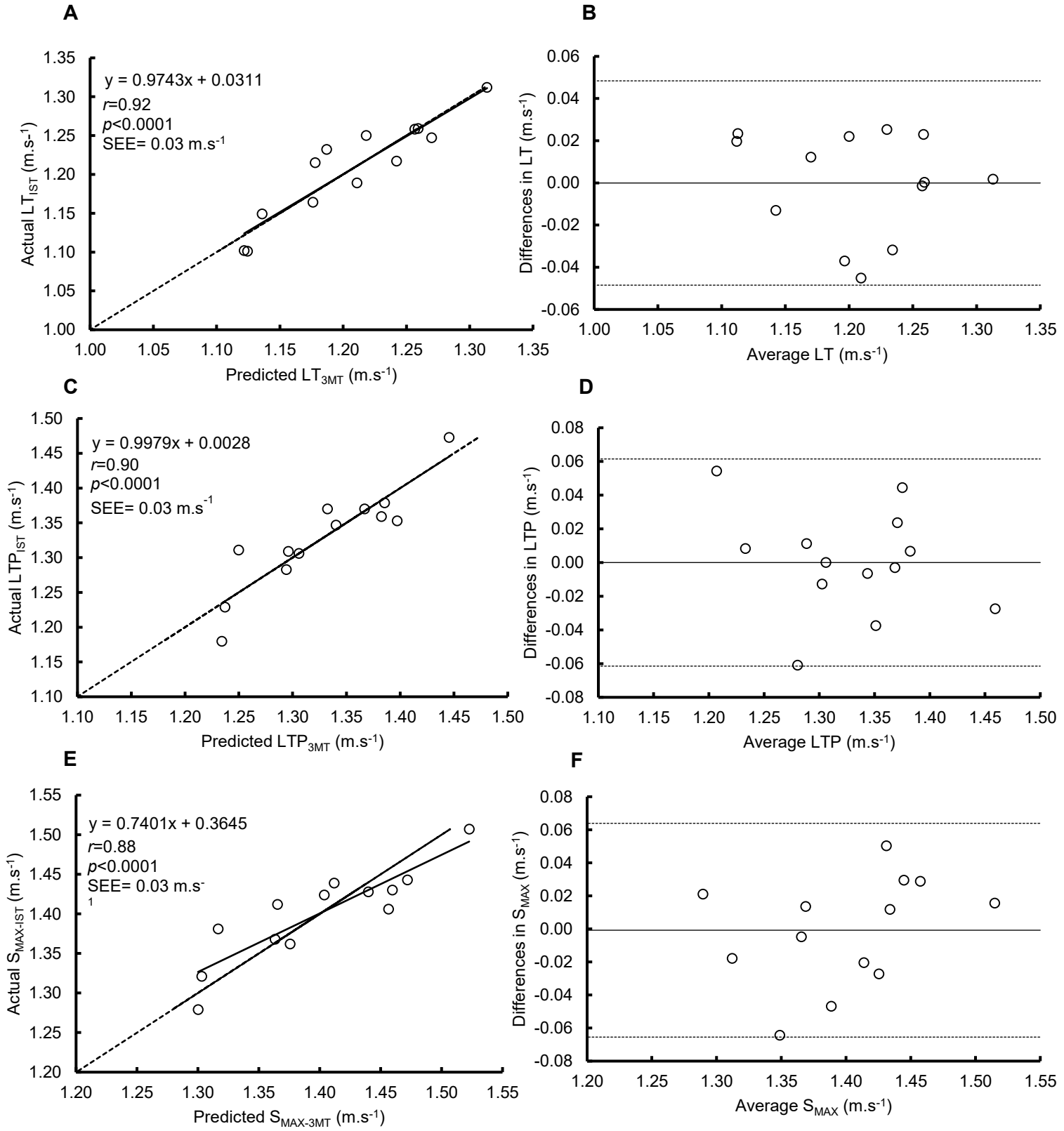
	Speed (m.s ⁻¹)	95% CI	ES	SEE (%)	<i>r</i> (95% CI)	Bias ± SD	95% LOA
LT_{50BBM} vs LT_{IST}	1.11 ± 0.08*	0.06 to 0.14	-1.44	0.05 (4.4)	0.63 ^a (0.11 to 0.87)	-0.10 ± 0.06 ^b	-0.23 to 0.02 ^c
LT_{40BBM} vs LT_{IST}	1.17 ± 0.07*	0.01 to 0.08	-0.60	0.05 (4.1)	0.68 ^a (0.20 to 0.89)	-0.04 ± 0.06 ^b	-0.15 to 0.07 ^c
CS_{30BBM} vs CS_{3MT}	1.23 ± 0.07‡	0.10 to 0.15	-1.82	0.05 (3.5)	0.76 ^a (0.36 to 0.92)	-0.12 ± 0.05 ^b	-0.22 to -0.03 ^c
CS_{20BBM} vs CS_{3MT}	1.29 ± 0.07‡	0.04 to 0.09	-0.96	0.04 (3.3)	0.79 ^a (0.41 to 0.93)	-0.06 ± 0.04 ^b	-0.15 to 0.02 ^c
LTP_{30BBM} vs LTP_{IST}	1.23 ± 0.07†	0.08 to 0.12	-1.41	0.04 (2.8)	0.87 ^a (0.61 to 0.96)	-0.10 ± 0.04 ^b	-0.17 to -0.03 ^c
LTP_{20BBM} vs LTP_{IST}	1.29 ± 0.07†	0.02 to 0.06	-0.57	0.03 (2.6)	0.89 ^a (0.67 to 0.97)	-0.04 ± 0.03 ^b	-0.10 to 0.02 ^c

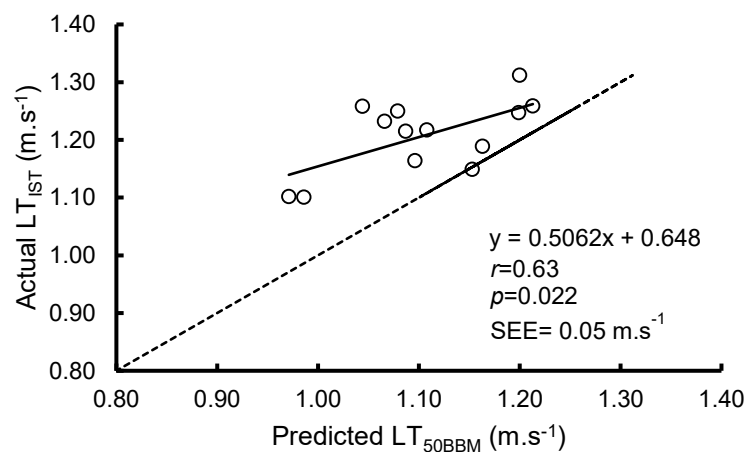
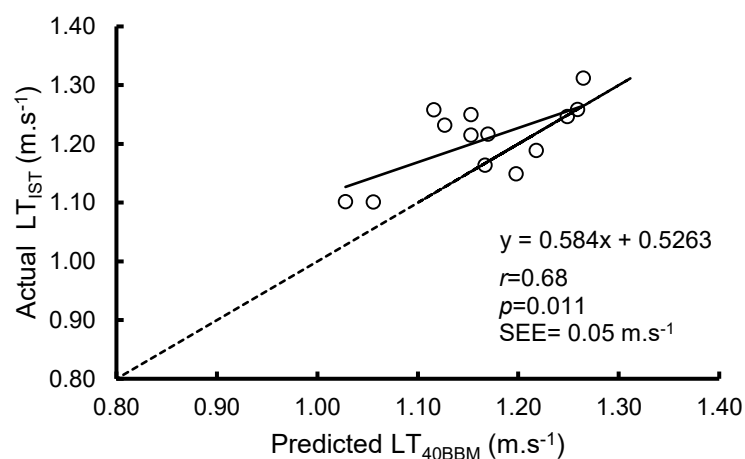
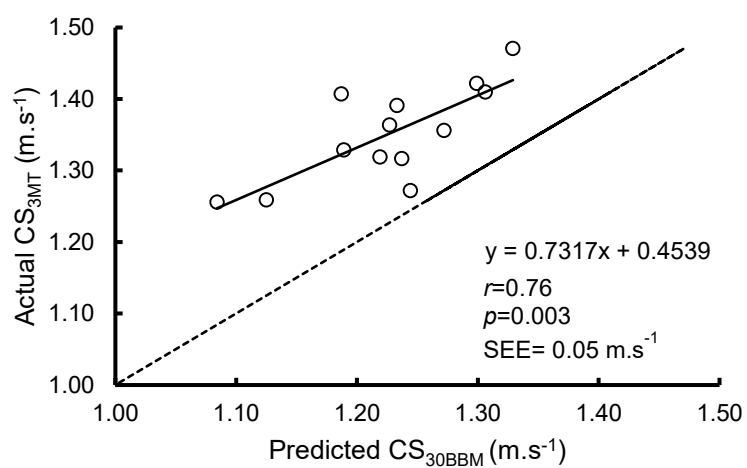
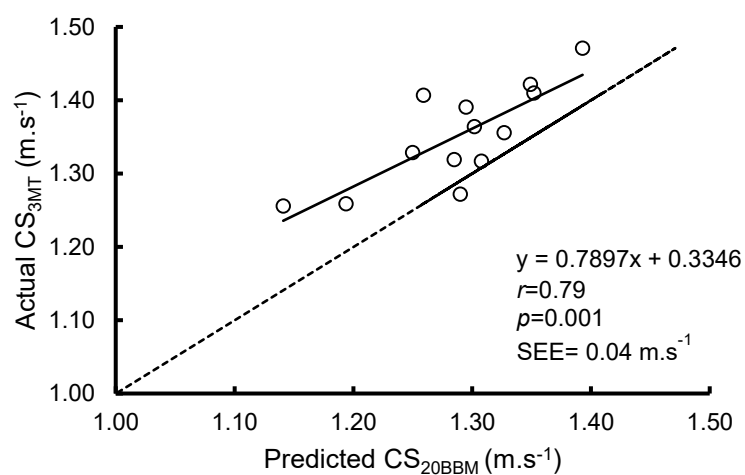
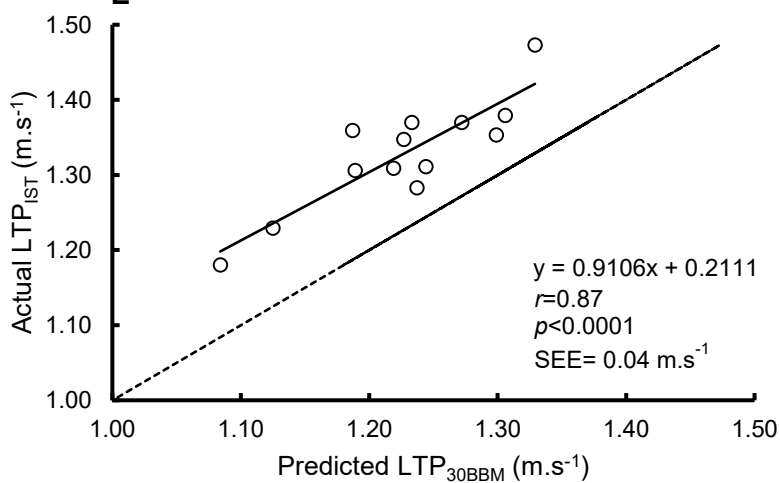
*40 and 50 beats below maximal heart rate (BBM) were used to derive the speed at LT; 20 and 30 BBM were used to derive the speed at LTP and CS; * $p < 0.02$ compared to LT_{IST}; † $p < 0.001$ compared to LTP_{IST}; ‡ $p < 0.0001$ compared to CS_{3MT}; ^a $p < 0.03$ correlation (r); ^b $p < 0.05$ significantly biased, ^c limits of agreement (LOA) outside of the acceptable threshold of 2%; SEE, standard error of estimate; ES, effect size; CI, confidence interval

Table 5. Comparisons of the heart rate at lactate threshold (LT) and lactate turnpoint (LTP) derived from the incremental step test (IST) and the BBM

	HR (bpm)	95% CI	ES	SEE (%)	<i>r</i> (95% CI)	Bias \pm SD	95% LOA
LT_{50BBM} vs LT_{IST}	147 \pm 8*	11 to 22	-1.62	10 (5.9)	0.64 ^a (0.13 to 0.88)	-17 \pm 9 ^b	-35 to 2 ^c
LT_{40BBM} vs LT_{IST}	157 \pm 8*	1 to 12	-0.63	10 (5.9)	0.64 ^a (0.13 to 0.88)	-7 \pm 9 ^b	-25 to 12 ^c
LTP_{30BBM} vs LTP_{IST}	167 \pm 8†	14 to 20	-1.91	6 (3.2)	0.84 ^a (0.53 to 0.95)	-17 \pm 5 ^b	-28 to -7 ^c
LTP_{20BBM} vs LTP_{IST}	177 \pm 8†	4 to 10	-0.79	6 (3.2)	0.84 ^a (0.53 to 0.95)	-7 \pm 5 ^b	-18 to 4 ^c

*40 and 50 beats below maximal heart rate (BBM) were used to derive the heart rate (HR) at LT; 20 and 30 BBM were used to derive the HR at LTP; * $p < 0.03$ compared to LT_{IST}, † $p < 0.0001$ compared to LTP_{IST}; ^a $p < 0.02$ correlation (r); ^b $p < 0.05$ significantly biased; ^c limits of agreement (LOA) outside of the acceptable threshold of 3%; bpm, beat per minute; SEE, standard error of estimate; ES, effect size; CI, confidence interval



A**B****C****D****E****F**